On the Interpretation of the Electroweak Precision Data

†

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Abstract

The recent precision electroweak data on Γ^l, $\bar{s}_W^2$ and M_W/M_Z are compared with the tree-level and the dominant-fermion-loop as well as the full one-loop standard-model predictions. While the tree-level predictions are ruled out, the dominant-fermion-loop predictions, defined by using $\alpha(M_Z^2) \cong 1/128.9$ in the tree-level formulae, as well as the full one-loop predictions are consistent with the experimental data. Deviations from the dominant-fermion-loop predictions are quantified in terms of an effective Lagrangian containing three additional parameters which have a simple meaning in terms of $SU(2)$ symmetry violation. The effective Lagrangian yields the standard one-loop predictions for specific values of these parameters, which are determined by m_t and m_H.

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To start with, in figs. 1a, b, c, we show the three projections of the three-dimensional, 68 % C.L. volume defined by the data in $(M_W/M_Z, \bar{s}_W^2, \Gamma_l)$-space in comparison with the simple-minded standard-model [1] tree-level prediction obtained from [1] [2]

$$
\begin{aligned}
\bar{s}_W^2(1-\bar{s}_W^2) &= \frac{\pi\alpha(0)}{\sqrt{2}G_\mu M_Z^2}, \\
\frac{M_{W^\pm}^2}{M_Z^2} &= 1-\bar{s}_W^2, \\
\Gamma_l &= \frac{G_\mu M_Z^3}{24\pi\sqrt{2}}(1+(1-4\bar{s}_W^2)^2)
\end{aligned} \tag{1}
$$

by using

$$
\begin{aligned}
\alpha(0) &= 1/137.0359895(61) \\
G_\mu &= 1.16639(2)10^{-5}GeV^{-2} \\
M_Z &= 91.187 \pm 0.007 GeV
\end{aligned} \tag{2}
$$

as input parameters. The data on $\bar{s}_W^2$ and Γ_l are the average values of the results of the four LEP experiments presented at the Marseille conference [2, 3]. The value of $\bar{s}_W^2$ is obtained from the ratio of the vector and axial-vector couplings of the Z_0 to leptons, g_V/g_A, via

$$\bar{s}_W^2 = \frac{1}{4}(1-\frac{g_V}{g_A}), \tag{3}$$

where g_V/g_A is deduced from all asymmetries at $\sqrt{s} = M_Z$,

$$
\begin{aligned}
g_V/g_A(\text{all asymmetries}) &= 0.0712 \pm 0.0028, \\
\bar{s}_W^2 &= 0.2322 \pm 0.0007.
\end{aligned} \tag{4}
$$

The leptonic width measured at LEP is given by

$$\Gamma_l = 83.79 \pm 0.28 MeV, \tag{5}$$

where lepton universality is assumed, and the ratio

$$\frac{M_W}{M_Z} = 0.8798 \pm 0.0028 \tag{6}$$

is given by CDF and UA2 data [4]

As seen from figs. 1a, b, c the tree-level prediction (1) is clearly ruled out by the data.

In 1988, as a strategy for the analysis of Z_0 precision data, it was suggested [5] "to isolate and to test directly the "new physics" of boson loops and other new phenomena by comparing

[1] We use the standard notation, M_W and M_Z for the masses of the charged and neutral weak boson, respectively, $\bar{s}_W^2$ for the square of the weak leptonic mixing angle measured at $\sqrt{s} = M_Z$ and Γ_l for the leptonic width of the Z_0, etc.

[2] We confine our analysis to the mentioned observables, as these are particularly simple ones which do not involve important hadronic (gluonic) effects.

with and looking for deviations from the predictions of the dominant-fermion-loop calculations". The dominant-fermion-loop predictions are simply obtained by the replacement[3]

$$\alpha(0) \rightarrow \alpha(M_Z^2) = 1/128.87 \pm 0.12 \tag{7}$$

in (1). The replacement (7) takes care of the dominant radiative corrections due to the logarithms of widely different scales (masses of the light fermions and the Z° mass). The correction due to the replacement (7) is precisely calculable as a pure QED [4] effect, and, consequently, it is independent of any hypothesis on the "new physics" (i.e., the empirically untested physics) of the interactions of the vector bosons with each other entering bosonic loop corrections and the properties of the Higgs particle or, from the point of view of local gauge symmetry, the nature of the electroweak symmetry breaking.

Accordingly, in our second step, in figs. 2a,b,c, we take a closer look at the data contours and compare them with predictions of the dominant-fermion-loop calculations (indicated by the symbol "star" in figs. 2a,b,c) and the full one-loop predictions thus refining and extending a previous analysis [7] based on the $'89$ LEP data. The lines in figures 2a,b,c, give the predictions of the one-loop results for fixed values of $m_H = 100, 300$ and $1000 GeV$, treating m_{top} as a parameter as indicated. These predictions were calculated by using the ZFITTER program [8]. They are in agreement with calculations based on refs. [7, 9]. From figs. 2a,b,c, we conclude:

1. The data at 68 % C.L. are consistent with the dominant-fermion-loop results.[5]

2. The data put a strong bound on deviations from the dominant-fermion-loop prediction, independently of the origin (standard or non-standard) of such additional contributions.

3. The data are in agreement with the full one-loop standard-model predictions which extend our present empirical knowledge by introducing non-Abelian bosonic self-interactions, at the same time assuring renormalizability of the theory at the expense of postulating the existence of the Higgs scalar particle (apart from introducing the top quark).

Evidently, apart from discovering the top quark and determining its mass, a direct measurement of the (trilinear and even quadrilinear) couplings of the vector bosons to each other [13] and a discovery of the Higgs particle seems indispensable for a full verification of the present electroweak theory.

The agreement between theory and experiment in figs. 2a,b,c is (obviously) far from trivial. This is best appreciated by reminding oneself of the pre-UA1,-UA2 and pre-LEP era. In 1978, it was pointed out by Bjorken and by Hung and Sakurai [14] that the experimental data

[3] In ref. [5], the term "dominant-fermion-loop" includes the loop contribution of a top quark of mass $30 GeV \leq m_t \leq 200 GeV$. Compare note added in proof for a discussion of the top-quark effect.

[4] Strictly speaking, this holds for lepton loops. The vacuum polarization due to quarks requires calculations based on the data on $e^+e^- \rightarrow$ hadrons via dispersion relations in order to incorporate hadronic (QCD) corrections. The uncertainties in the input data lead to the error in (7). Compare ref. [6].

[5] This was also noted and strongly emphasized by Novikov, Okun and Vysotsky [10], who showed in addition [11] that the experimental results for the LEP observables involving hadronic Z^0 decays are consistent with the $\alpha(M_Z^2)$ tree-level formula. Compare also ref. [12]. Consistency of the data with both, the dominant-fermion-loop as well as the full one-loop theoretical predictions is not entirely unexpected, as it was repeatedly stressed [5, 7] that the experimental errors to be expected in the high-precision LEP measurements will at most marginally allow to discriminate between dominant-fermion-loop predictions and full one-loop results.

on neutral-current interactions then available did not necessarily require the validity of the $SU(2)_L \times U(1)_Y$ standard theory. It was shown that a Lagrangian based on global $SU(2)$ weak-isospin symmetry broken by γW^3 mixing could also explain the NC data, and it was stressed that high-energy (LEP, SLC) data were necessary to rule out this four-free-parameter effective-Lagrangian alternative. The high-precision data available now allow one to precisely investigate to what degree of accuracy any $SU(2)_L \times U(1)_Y$ violation of the Hung-Sakurai type is actually excluded.

Somewhat more generally, we propose to analyse the body of experimental data on $M_W/M_Z, \bar{s}_W^2$ and Γ_l on the basis of the effective Lagrangian (written in the physical base)

$$\begin{aligned} L_C &= -\frac{1}{2}W_+^{\mu\nu}W_{\mu\nu}^- + \frac{g_{W^\pm}}{\sqrt{2}}(j_\mu^+ W_+^\mu + h.c.) + M_{W^\pm}^2 W_\mu^+ W_-^\mu, \\ L_N &= -\frac{1}{4}A^{\mu\nu}A_{\mu\nu} - \frac{1}{4}Z_0^{\mu\nu}Z_{\mu\nu}^0 + \frac{1}{2}\frac{M_{W^0}^2}{1-\bar{s}_W^2(1-\epsilon)}Z_0^\mu Z_\mu^0 \\ &\quad + eJ_{em}^\mu A_\mu + \frac{g_{W^0}}{\sqrt{1-\bar{s}_W^2(1-\epsilon)}}(J_3^\mu - \bar{s}_W^2 J_{em}^\mu)Z_\mu^0, \end{aligned} \tag{8}$$

with the constraint

$$g_{W^0}^2 = \frac{e^2}{\bar{s}_W^2}(1-\epsilon), \tag{9}$$

by which the number of parameters is reduced to *six* independent ones. The parameter e in (8) refers to the electric charge measured at the scale $M_Z, e = e(M_Z^2)$. The Lagrangian (8) contains $SU(2)_L$ violation via mixing à la Hung-Sakurai [6]

$$\epsilon W^{3\mu\nu}B_{\mu\nu}, \tag{10}$$

quantified by the parameter ϵ and $SU(2)$ violation via discriminating $g_{W^\pm}$ from g_{W^0}, quantified by the parameter y, in

$$\begin{aligned} g_{W^\pm}^2 &= y g_{W^0}^2, \\ &= (1+\Delta y)g_{W^0}^2. \end{aligned} \tag{11}$$

A violation of global $SU(2)$ symmetry in the mass term is introduced and quantified by discriminating $M_{W^\pm}$ from M_{W^0} in

$$\begin{aligned} M_{W^\pm}^2 &= x M_{W^0}^2, \\ &= (1+\Delta x)M_{W^0}^2. \end{aligned} \tag{12}$$

Altogether, the standard number of *three* input parameters is thus supplemented by *three* parameters quantifying *all* potential sources of $SU(2)$ violation. We note that any additional violation of $SU(2)$ symmetry can be removed if a redefinition of the fields is accompanied by a readjustment of the $SU(2)$-violating parameters introduced in (10),(11),(12).

A further remark on the significance of Lagrangian (8) may be appropriate. It contains a twofold physical interpretation:

[6] This is explicitly seen by performing appropriate transformations to the BW^3 or to the γW^3 base. Compare refs. [7, 15, 16].

1. The Lagrangian (8) effectively describes the one-loop standard-model electroweak interactions of the leptons [7] with the vector bosons at the $Z^0(W^\pm)$ mass scale, provided x, y and ϵ are appropriately specified in terms of m_t and m_H (see below).

2. Without employing the concept of spontaneous symmetry breaking, the effective Lagrangian (8) for $x = y = 1$ but $\epsilon \neq 0$ is obtained by assuming breaking of global $SU(2)$ symmetry via current mixing [14]. A priori, from this point of view, ϵ may differ appreciably from $\epsilon = 0$. The strong empirical constraints on ϵ to be given below reduce ϵ to the order of magnitude of standard radiative corrections and strongly restrict appreciable non-standard effects, thus empirically verifying the "unification condition" [14] $\epsilon \cong 0$ to a high level of accuracy. The additional parameters $\Delta x \neq 0, \Delta y \neq 0$ take into account additional potential sources of $SU(2)$ violation.

On the basis of the effective Lagrangian (8), the modified relations (1) now read

$$\begin{aligned} \bar{s}_W^2(1-\bar{s}_W^2) &= \frac{\pi\alpha(M_Z)}{\sqrt{2}G_\mu M_Z^2}\frac{y}{x}(1-\epsilon)\frac{1}{(1+\frac{\bar{s}_W^2}{1-\bar{s}_W^2}\epsilon)}, \\ \frac{M_{W^\pm}^2}{M_Z^2} &= (1-\bar{s}_W^2)x(1+\frac{\bar{s}_W^2}{1-\bar{s}_W^2}\epsilon), \\ \Gamma_l &= \frac{G_\mu M_Z^3}{24\pi\sqrt{2}}(1+(1-4\bar{s}_W^2)^2)\frac{x}{y}(1+\frac{3\alpha}{4\pi}), \end{aligned} \tag{13}$$

where a QED correction factor is included in the expression for Γ_l in agreement with the definition of Γ_l used in the analysis of the data [2, 3]. Keeping only terms linear in $\epsilon, \Delta x, \Delta y$, one obtains from (13)[8]

$$\begin{aligned} \bar{s}_W^2 &= s_0^2\left[1-\frac{1}{c_0^2-s_0^2}\epsilon-\frac{c_0^2}{c_0^2-s_0^2}(\Delta x-\Delta y)\right], \\ \frac{M_W}{M_Z} &= c_0\left[1+\frac{s_0^2}{c_0^2-s_0^2}\epsilon+\frac{c_0^2}{2(c_0^2-s_0^2)}(\Delta x-\Delta y)+\frac{1}{2}\Delta y\right], \\ \Gamma_l &= \Gamma_l^{(0)}\left[1+\frac{8s_0^2(1-4s_o^2)}{(c_0^2-s_0^2)(1+(1-4s_0^2)^2)}\epsilon+\frac{2(c_0^2-s_0^2-4s_0^4)}{(c_0^2-s_0^2)(1+(1-4s_0^2)^2)}(\Delta x-\Delta y)\right], \end{aligned} \tag{14}$$

where

$$\begin{aligned} s_0^2(1-s_0^2) \equiv c_0^2 s_0^2 &= \tfrac{\pi\alpha(M_Z^2)}{\sqrt{2}G_\mu M_Z^2}, \\ \Gamma_l^{(0)} &= \tfrac{\alpha(M_Z^2)M_Z}{48 s_0^2 c_0^2}\left[1+(1-4s_0^2)^2\right]\left(1+\tfrac{3\alpha}{4\pi}\right). \end{aligned} \tag{15}$$

In view of future analysis of empirical data, it will be useful to explicitly give the inversion of (14),

[7] For quarks, (8) has to be generalized in a manner such that the large non-universal corrections due to $Z \to b\bar{b}$ decay [17] can be accomodated.

[8] It was checked that the *relative* errors in $\bar{s}_W^2, M_W/M_Z$ and Γ_l introduced by the linear approximation are of the order of 10^{-4} for the relevant range of values of $\epsilon, \Delta x$, and Δy.

$$\begin{aligned}
\epsilon &= \frac{1}{(c_0^2-s_0^2)^2+4s_0^4} \\
&\quad \left[-\frac{c_0^2-s_0^2-4s_0^4}{s_0^2}\bar{s}_W^2-\frac{c_0^2(1+(1-4s_0^2)^2)}{2\Gamma_l^{(0)}}\Gamma_l+2c_0^2-5s_0^2+8c_0^2s_0^4\right], \\
\Delta x-\Delta y &= \frac{1}{(c_0^2-s_0^2)^2+4s_0^4}\left[4(1-4s_0^2)\bar{s}_W^2+\frac{1+(1-4s_0^2)^2}{2\Gamma_l^{(0)}}\Gamma_l-1+8s_0^4\right], \qquad (16) \\
\Delta y &= \frac{-2}{(c_0^2-s_0^2)^2+4s_0^4} \\
&\quad \left[(c_0^2-5s_0^2)\bar{s}_W^2+\frac{c_0^2(1+(1-4s_0^2)^2)}{4\Gamma_l^{(0)}}\Gamma_l-\frac{1}{2}+\frac{3}{2}s_0^2+4s_0^6\right]+2\left(\frac{M_W}{M_Z c_0}-1\right).
\end{aligned}$$

The dominant-fermion-loop prediction (7) in the Lagrangian (8) (with (9), (11), (12)) simply corresponds to $\epsilon=\Delta x=\Delta y=0$, while the one-loop induced standard-model corrections are described by Lagrangian (8) for special values of ϵ, x, y, which depend on the top-mass, m_t, and the Higgs mass, m_H. Using the results of, e.g., [5], one finds for the dominant contributions to $\Delta x-\Delta y, \Delta y$ and ϵ

$$\begin{aligned}
\Delta x-\Delta y &= \frac{3G_\mu m_t^2}{8\sqrt{2}\pi^2}-\frac{G_\mu M_W^2}{2\pi^2\sqrt{2}}\frac{3}{2}\frac{s_0^2}{c_0^2}\ln\frac{m_H}{M_Z}+\cdots, \\
\Delta y &= \frac{G_\mu M_W^2}{2\sqrt{2}\pi^2}\ln\frac{m_t}{M_Z}+\cdots, \qquad (17) \\
\epsilon &= \frac{G_\mu M_W^2}{6\pi^2\sqrt{2}}\ln\frac{m_t}{M_Z}-\frac{G_\mu M_Z^2 c_0^2}{12\pi^2\sqrt{2}}\ln\frac{m_H}{M_Z}+\cdots.
\end{aligned}$$

Comparison with ref. [12] reveals that our parameters defined in terms of $SU(2)$-symmetry properties of electroweak interactions are simple linear combinations of the parameters $\epsilon_{N1}, \epsilon_{N2}, \epsilon_{N3}$ introduced in [12][9] by the requirement of isolating the quadratic m_t dependence, i.e.,

$$\begin{aligned}
\Delta x-\Delta y &= \epsilon_{N1}, \\
\Delta y &= -\epsilon_{N2}, \qquad (18) \\
\epsilon &= -\epsilon_{N3}.
\end{aligned}$$

Relations (18) establish the meaning of the parameters $\epsilon_{N1}, \epsilon_{N2}, \epsilon_{N3}$ with respect to $SU(2)$-symmetry properties of the electroweak interactions.

By solving (13) for $\epsilon, \Delta x-\Delta y, \Delta y$ and expanding around the experimental values for $M_W/M_Z, \bar{s}_W^2, \Gamma_l$ or, alternatively, by using (16), one obtains linear relations for $\epsilon, \Delta x-\Delta y, \Delta y$ in terms of $M_W/M_Z, \bar{s}_W^2, \Gamma_l$. By inserting the experimental data, one can deduce the experimental bounds on $\epsilon, \Delta x-\Delta y$, and Δy.

In figs. 3a, b, c, we show the resulting projections of the 68 % C.L. volume in $(\epsilon, \Delta y, \Delta x-\Delta y)$-space on the planes $\Delta y = const, \epsilon = const$ and $\Delta x-\Delta y = const$, respectively, in comparison with the $\alpha(M_Z^2)$-tree-level point ($\epsilon=\Delta x-\Delta y=\Delta y=0$) and

[9] For related work based on parameters somewhat different from the ones in (18), we refer to the list of references in [12].

the one-loop-standard-model predictions. As expected from figs. 2a,b,c, the $SU(2)$-symmetry point[10], $\epsilon = \Delta x - \Delta y = \Delta y = 0$ as well as the one-loop predictions lie within the ellipsoid. As a new result from figs. 3a, b, c, in comparison with figs. 2a, b, c, one can read off the restrictions on the magnitude of the departure from $SU(2)$ symmetry allowed by the experimental data. The absolute values of $\epsilon, \Delta x - \Delta y$, and Δy at 68 % C.L. are restricted to the level of (10 to 20) $\cdot\, 10^{-3}$ or 1 to 2 per cent.

As seen in Figs. 3a,b,c, the one-loop standard model for $m_t \gtrsim 110 GeV$ yields approximately constant values of $\epsilon \cong -6.5 \cdot 10^{-3}$ and $\Delta y \cong +6.5 \cdot 10^{-3}$, while, as a consequence of the quadratic m_t dependence, the quantity $\Delta x - \Delta y$ varies significantly, when m_t is varied between 100 and $200 GeV$.

In conclusion, the high precision of the present data is apparent from the fact that the tree-level prediction based on the "wrong" value of $\alpha \equiv \alpha(0) \equiv 1/137$ is clearly ruled out, while the tree-level prediction obtained by inserting the "correct" value of $\alpha \equiv \alpha(M_Z^2) \cong 1/129$ is consistent with the experimental data. Deviations from the prediction based on $\alpha(M_Z^2)$ are indeed strongly constrained by the data. The parameters $\epsilon, \Delta x, \Delta y$ quantifying $SU(2)$-symmetry violations are constrained to the order of 0.01 to 0.02 at 68 % C.L. This is the order of magnitude of the standard one-loop weak corrections which depend on the magnitude of the mass of the top quark, the empirically unknown interactions of the vector bosons among each other and the existence of the Higgs scalar. The consistency between the data and the standard one-loop predictions strongly supports the validity of the standard theory, even though, in principle, any theory which supplies sufficiently small bosonic loops (assuming the existence of the top quark with a reasonable value of its mass) will be consistent with the available experimental information. By the end of the running of LEP at the Z^0 energy, the precision of the data can be envisaged to become even better than the distance between the dominant-fermion-loop point and the standard-model lines in figs. 2 and 3. Even though constraints on non-standard effects will become even stronger than at present, a direct investigation of the trilinear (and quadrilinear) couplings among the vector bosons and direct experimental evidence for the Higgs scalar will be indispensable for a full empirical verification of our present theory of the electroweak interactions.

Note added in proof.

The dominant-fermion-loop analysis of the present work did not take into account the direct experimental information on the properties of a (hypothetical) top quark. In particular, the lower bound on the mass, $m_t \geq 112 GeV$ [18] of a standard top quark was not taken into account. Even though the top quark has not been identified experimentally so far, strong arguments are available for its existence. Let us thus assume that a top quark of mass $m_t \geq 112 GeV$ exists and moreover that it has standard interactions with the electroweak vector bosons. As a consequence, the top-quark loop yields a well-known contribution to the electroweak observables which has to be taken into account in addition [5, 7] to the running of the electromagnetic coupling caused by the light leptons and quarks.

[10]The fact that the point $\epsilon = \Delta y = 0$ in fig. 3c lies at the outside edge of the ellipse (in distinction from the corresponding points in figs. 2 a,b,c) is related to the linearization procedure applied to (12) (and also used in (13)) when deriving the covariance matrix from the experimental data.

Taking into account the standard one-loop top contribution in addition to the contribution of the light leptons and quarks yields the short-dashed and long-dashed curves in figs. 2a,b,c and 3a,b,c. The short-dashed curve is calculated by using the asymptotically leading (quadratic and logarithmic) m_t dependence given in Eq. (17). The long-dashed curve takes into account the one-loop top-quark contribution exactly. From figs. 2a,b,c and 3a,b,c, we conclude:

1. The dominant-fermion-loop approximation, taking into account a standard "light" top quark of mass $m_t \cong 60 GeV$ to $m_t \cong 80 GeV$ in addition to the light fermions, is marginally consistent with the LEP precision data (disregarding the fact that the negative results of the direct searches provide a lower bound of $m_t \geq 112 GeV$).

2. The assumption of a standard top-loop contribution to the LEP observables combined with the lower bound of $m_t \geq 112 GeV$ from the direct top search leads to a (mild) discrepany between the dominant-fermion-loop predictions and the LEP precision data at 68 % C.L. (compare figs. 2a,b and, in particular, fig. 3a). Consistency of the existence of a very massive standard top quark with the LEP data thus requires (standard or non-standard) effects beyond the dominant fermion loops to contribute to the LEP observables.

In summary, exploiting the lower bound of $m_t \geq 112 GeV$ for a standard top-quark obtained in the direct top-quark search allows us to refine the conclusion of the present paper: consistency with the LEP precision data of the hypothesis of the existence of a heavy top quark with mass $m_t \geq 112 GeV$ and standard electroweak interactions, (marginally) requires the presence of (standard or non-standard) contributions to the LEP observables beyond the dominant fermion loops. In other words, under the mentioned hypotheses on the top quark, LEP is starting to "see" effects beyond the standard dominant fermion loops.

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Figure captions

Fig. 1: The experimental data for
a) the boson-mass ratio, M_M/M_Z, and the electroweak mixing angle, $\bar{s}_W^2$, deduced from all the asymmetries measured at $\sqrt{s} = M_Z$,
b) the leptonic width, Γ_l, of the Z° and $\bar{s}_W^2$
c) Γ_l and M_W/M_Z

are compared with the standard tree-level predictions based on $\alpha^{-1} \equiv \alpha(0)^{-1} \cong 137.036$. The ellipses are the projections of the 68 % C.L. ellipsoid defined by the data in $(M_W/M_Z, \bar{s}_W^2, \Gamma_l)$ space.

Fig. 2a,b,c: The same experimental data as in figs. 1a, b, c. The point denoted by the symbol "star" gives the standard tree-level predictions based on $\alpha^{-1} \equiv \alpha(M_Z^2)^{-1} = 1/128.87 \pm 0.12$. The long-dashed curve is obtained by taking into account the top-loop contribution (in addition to the light fermions yielding $\alpha(M_Z^2)$). The

corresponding short-dashed curve is calculated by approximating the top contribution according to Eq. (17). The standard-model full one-loop results are shown for Higgs-boson masses of $m_H = 100, 300$ and $1000 GeV$, varying the mass of the top quark in steps of $20 GeV$, as indicated. Note that the error bar shown at the $\alpha(M_Z^2)$ point denoted by the symbol "star" must also be applied to all other theoretical results shown in the figure.

Fig. 3a,b,c: The experimental restrictions (68% C.L.) on the paramters $\epsilon, \Delta x - \Delta y$ and Δy obtained by solving (13) or, alternatively, by using (16) and evaluating the result by inserting the experimental data for $M_W/M_Z, \bar{s}_W^2$ and Γ_l given in (4), (5), (6) and displayed in figs. 1 and 2. The theoretical curves correspond to the ones of figs. 2a,b,c.